U.S. MAGNET DEVELOPMENT PROGRAM

Development and First Test of the US-MDP 15 T Nb_3Sn Dipole Demonstrator MDPCT1

Fermilab APT seminar
August 15, 2019

Alexander Zlobin
US Magnet Development Program
Fermi National Accelerator Laboratory

Outline

- In June 2019 the HFM group at Fermilab has tested a new accelerator dipole magnet based on Nb_3Sn superconductor, which produced a world record field of 14.1 Tesla at 4.5 K.

- Outline
  - Magnet design and analysis
  - Magnet technology
  - Quench performance (training)
  - Field quality measurements and analysis
  - Conclusions and next steps

Acknowledgment

FNAL: I. Novitski, E. Barzi, J. Carmichael, G. Chlachidze, J. DiMarco, V.V. Kashikhin, S. Krave, C. Orozco, S. Stoynev, T. Strauss, M. Tartaglia, D. Turrioni, G. Velev, A. Rusy, S. Jonhson, J. Karambis, J. McQueary, L. Ruiz, E. Garcia

LBNL: S. Caspi, M. Juchno, M. Martchevskii

CERN: D. Schoerling, D. Tommasini

FEAC/UPATRAS: C. Kokkinos

US-MDP: G6 and TAC

This work was supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy and the US-MDP.

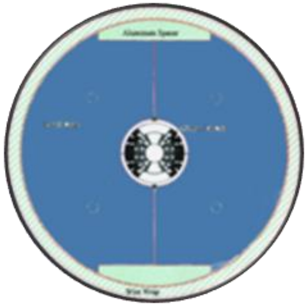
Introduction

- The 15 T dipole demonstrator project was initiated in 2015 at Fermilab in response to recommendations of the Particle Physics Project Prioritization Panel (also called P5) and HEPAP Accelerator R&D subpanel.
- In June 2016, after the Office of High Energy Physics at US-DOE created the national MDP to integrate accelerator magnet R&D in the United States and coordinate it with the international effort, this project became a key task of the MDP.
- In 2017 this effort received support also by the EuroCirCol program, making it a truly International endeavor.

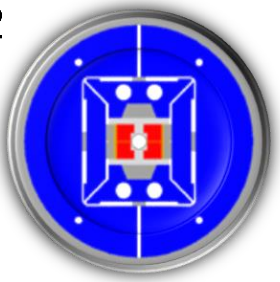
15 T dipole program goals

- Demonstration of 15+ T field level with Nb_3Sn superconductor
- Study and optimization of
  - magnet quench performance and mechanics
  - field quality
  - quench protection
  - Cost optimization
- Record Nb_3Sn dipole magnets:
  - D20 (LBNL, 1997): B_{max}=13.5 T @1.9K, 12.8 T @4.4K
  - HD2 (LBNL, 2008): B_{max}=13.8 T @4.5K

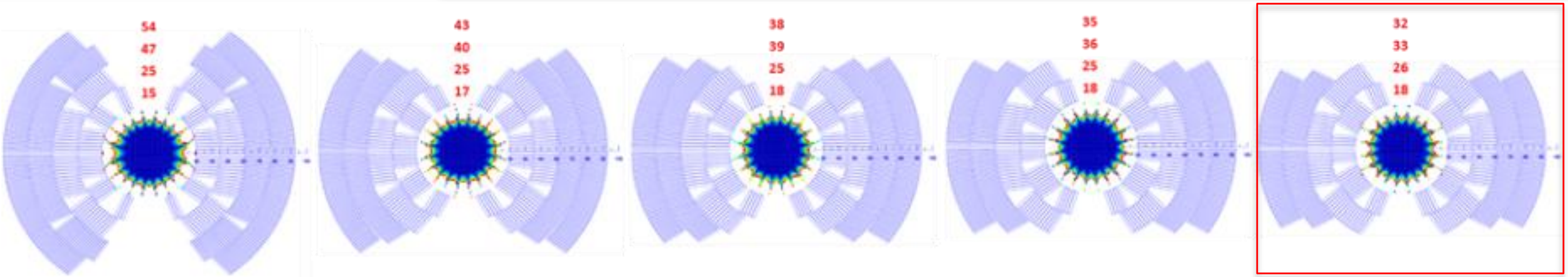
D20



HD2



15 T Dipole design selection

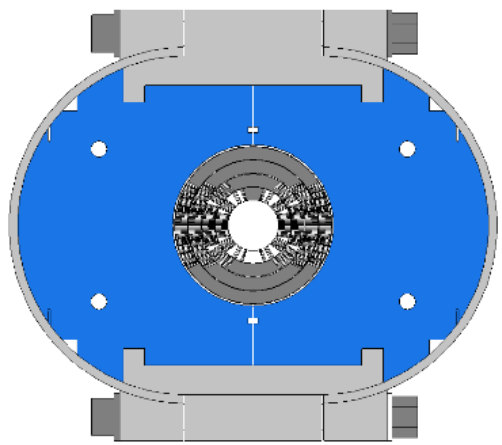


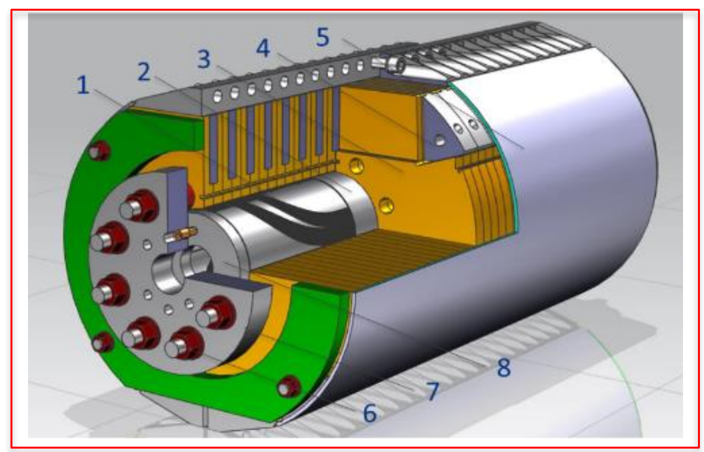
Coil (V.V. Kashikhin et al.):

- 60-mm aperture
- 4-layer graded cos-theta coil
- Selection criteria: B_{max}, FQ, forces, protection

Mechanical structure (I. Novitski et al.):

- Design 1: SS C-clamps and 20-mm thick SS skin
- Design 2: Al I-clamps and 12-mm thick SS skin
- Criteria: coil stress and strain



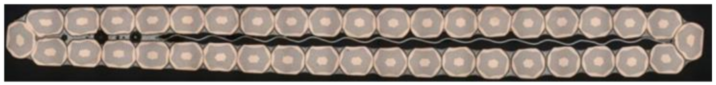


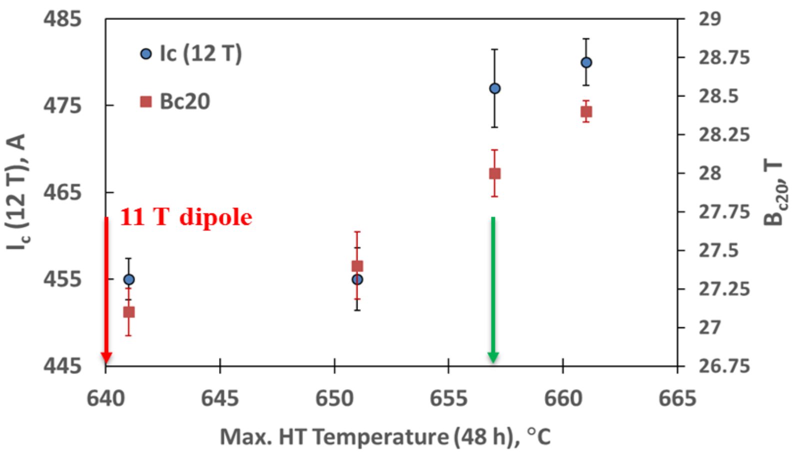
U.S. MAGNET DEVELOPMENT PROGRAM

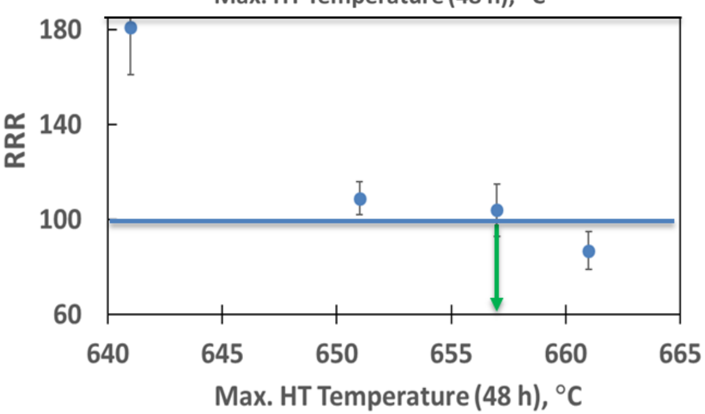
Nb_3Sn strands and cables

Courtesy E. Barzi and D. Turrioni

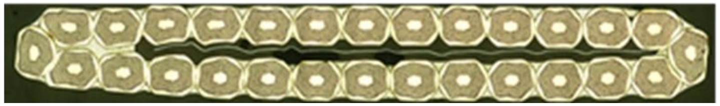
0.7 mm RRP108/127
40-strand cable with SS core

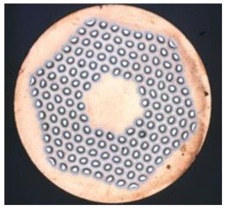


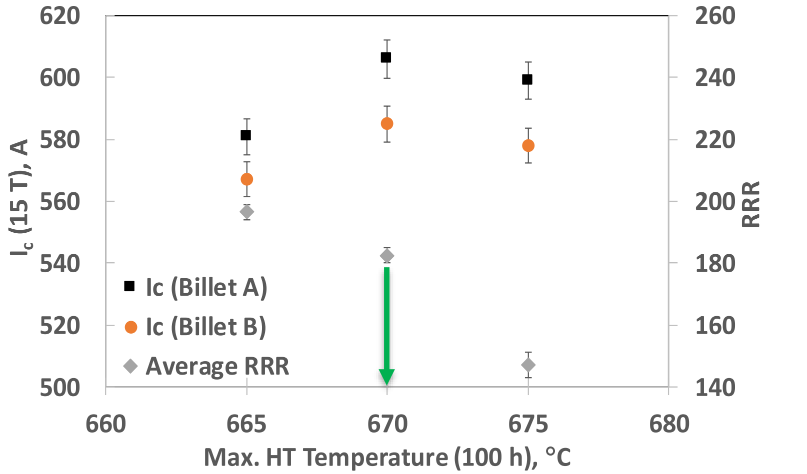




1 mm RRP150/169
28-strand cable with SS core

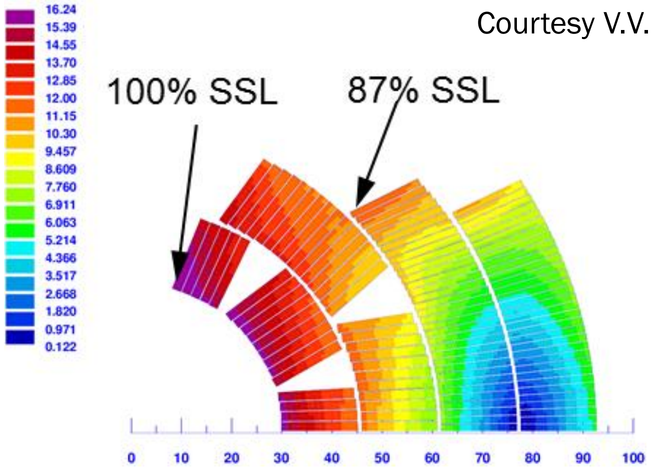


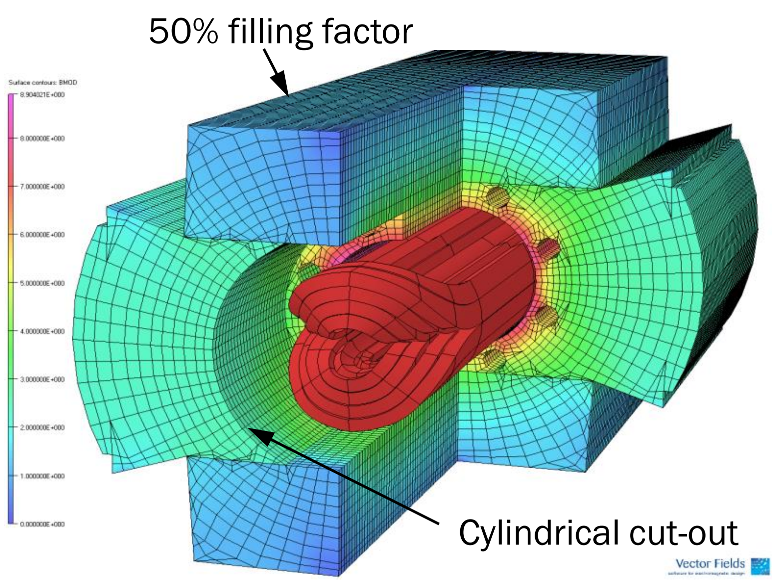


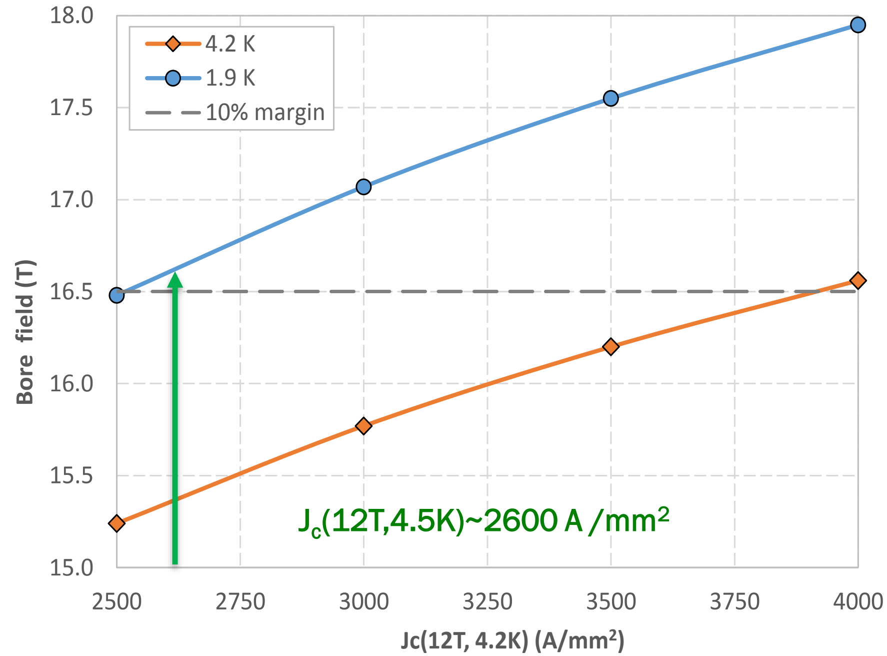


Magnet conductor limit

Courtesy V.V. Kashikhin



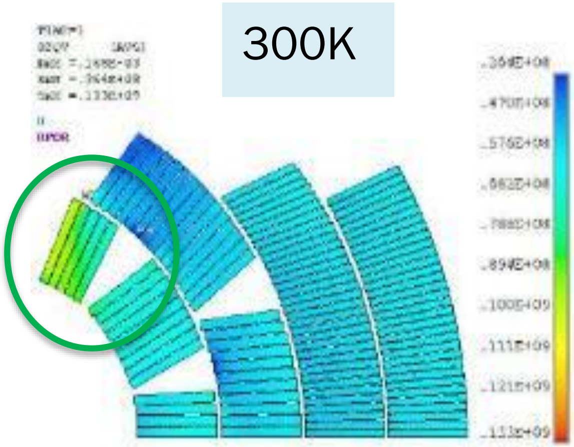




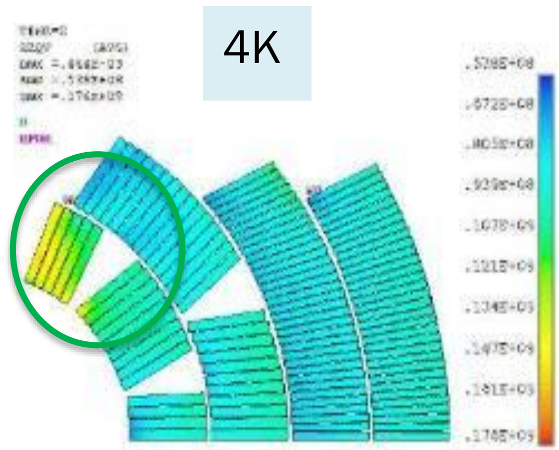
Magnet ***conductor limit*** for the wire J_c(12T,4.2K)~2.6 kA/mm^2

- B_{ap}=15.3T @4.5K
- B_{ap}=16.7T @1.9K

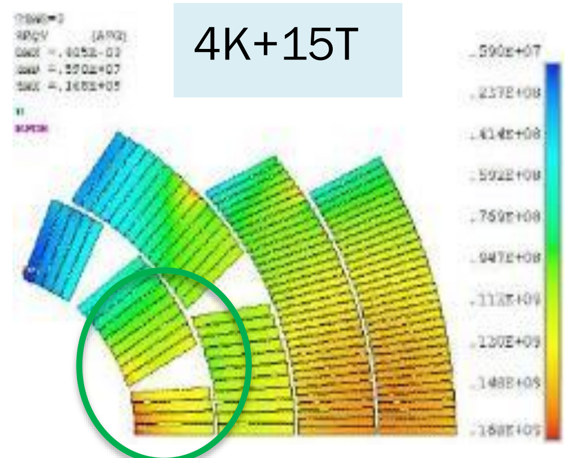
Magnet mechanical limit



S_{eqv}=133 MPa
Limit 150 MPa

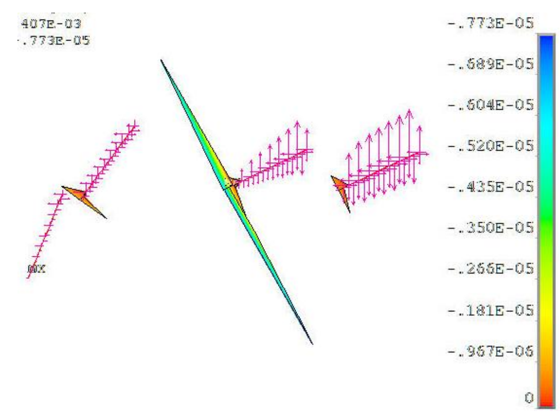


S_{eqv}=176 Mpa
Limit 200 MPa



S_{eqv}=168 Mpa
Limit 200 MPa

- **Magnet *design limit* is determined by the coil maximum stress and the pole turn separation from poles**
  - **independent FNAL and FEAC analysis**

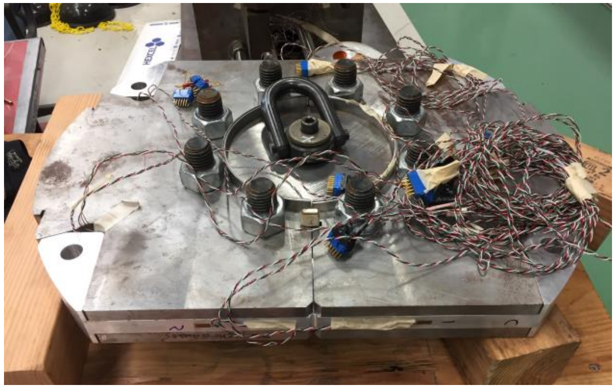


Courtesy I. Novitski

Mechanical limit for this design is 15 T!

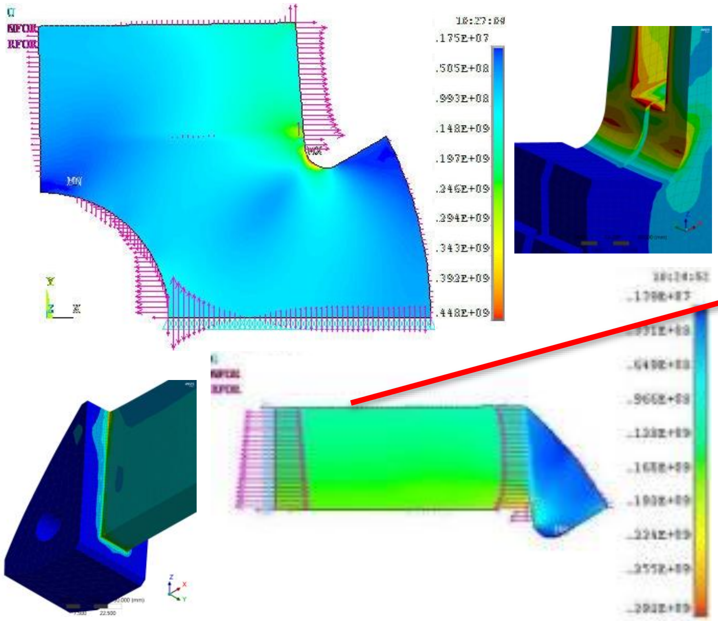
Mechanical Model Tests

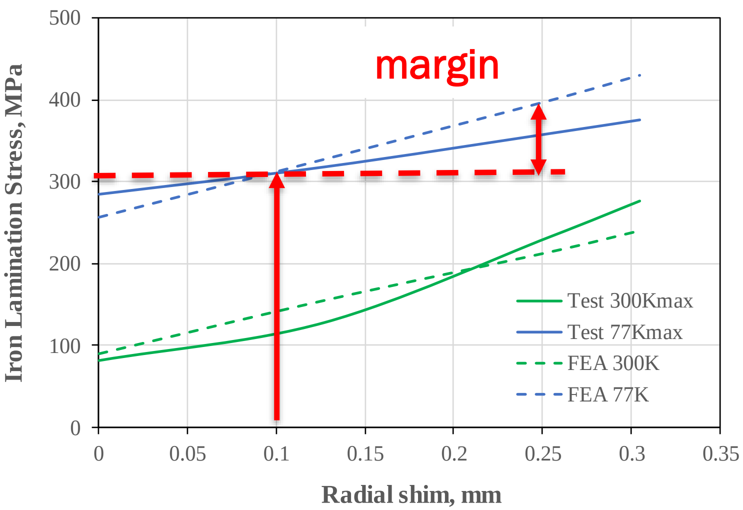
Courtesy I. Novitskiy and C. Orosco

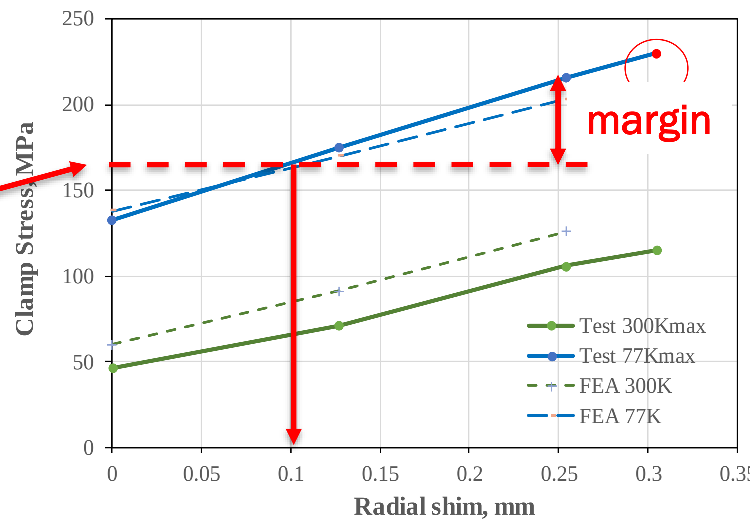


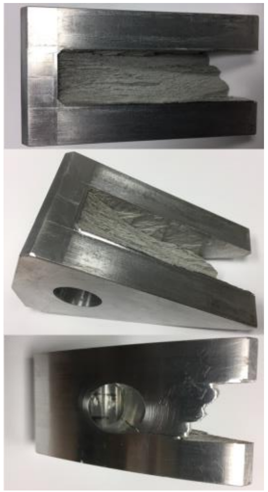
MM Goals:

- Test brittle yoke and clamps
- Validate the mechanical analysis
- Develop the coil pre-stress targets



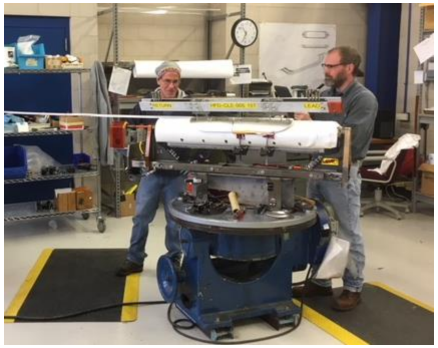






U.S. MAGNET DEVELOPMENT PROGRAM

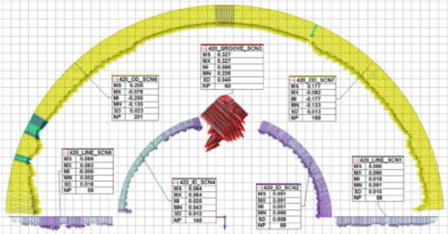
Coil fabrication, measurements and instrumentation



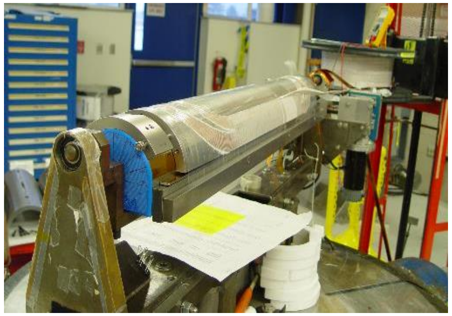
Coil winding and curing using ceramic binder

Coil reaction

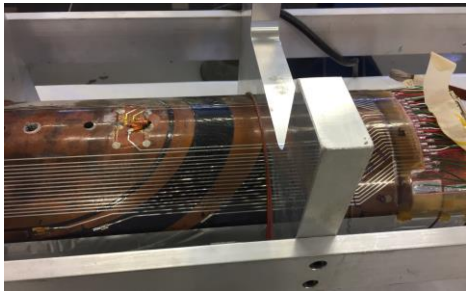
Coil lead splicing and epoxy impregnation



Coil size control, accuracy ~10 microns



Coil instrumentation

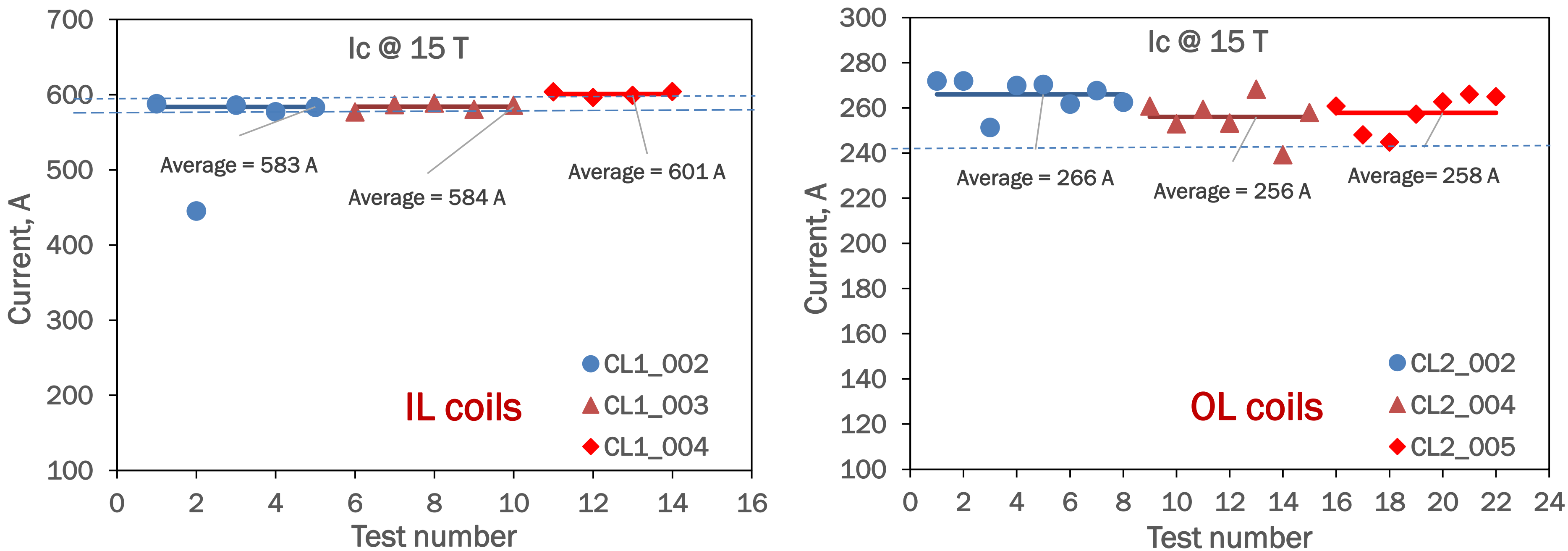


- Coil fabrication, measurement and instrumentation time ~3 months

U.S. MAGNET DEVELOPMENT PROGRAM

Witness sample data and magnet SSL

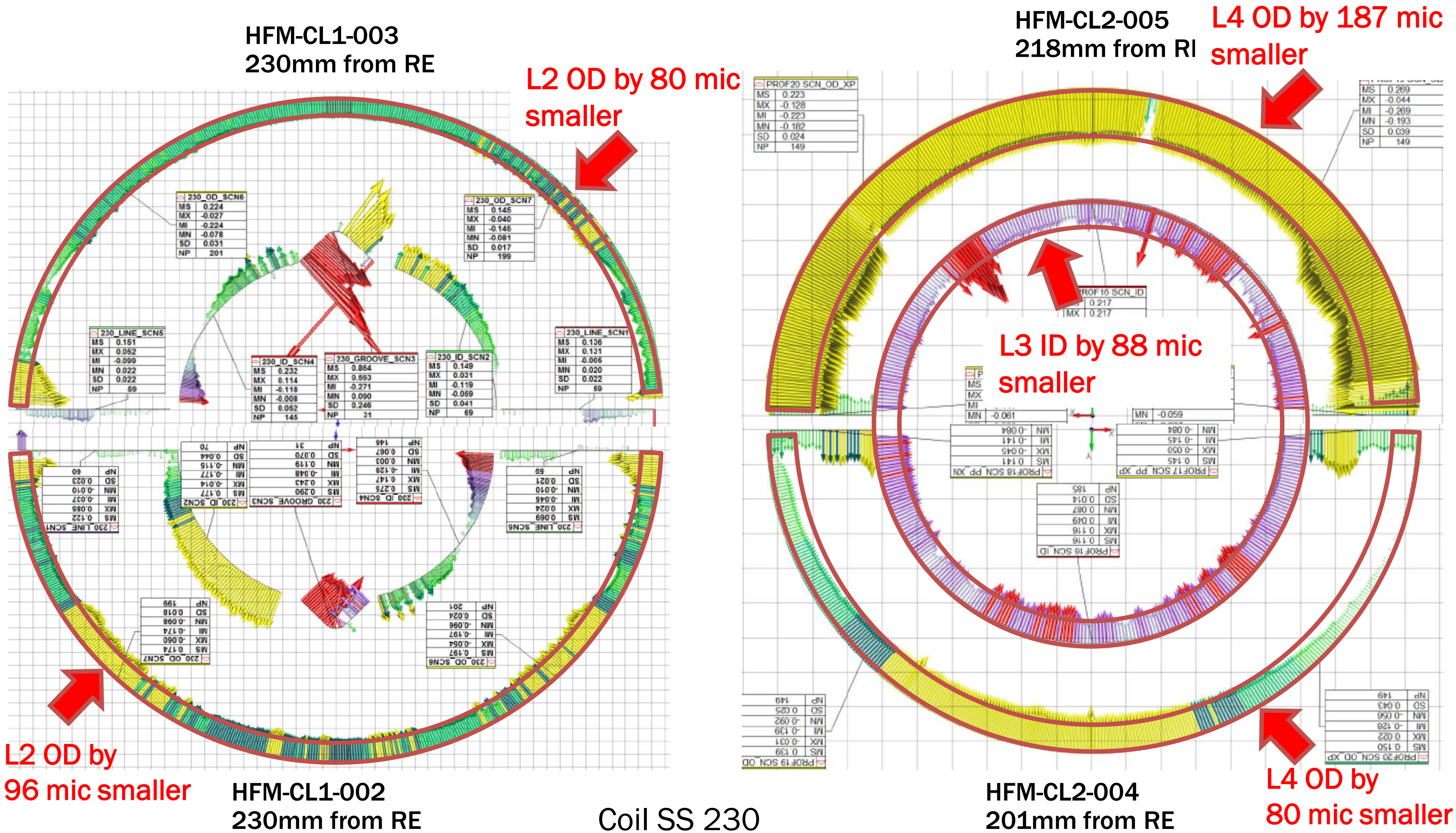
Courtesy E. Barzi and D. Turrioni



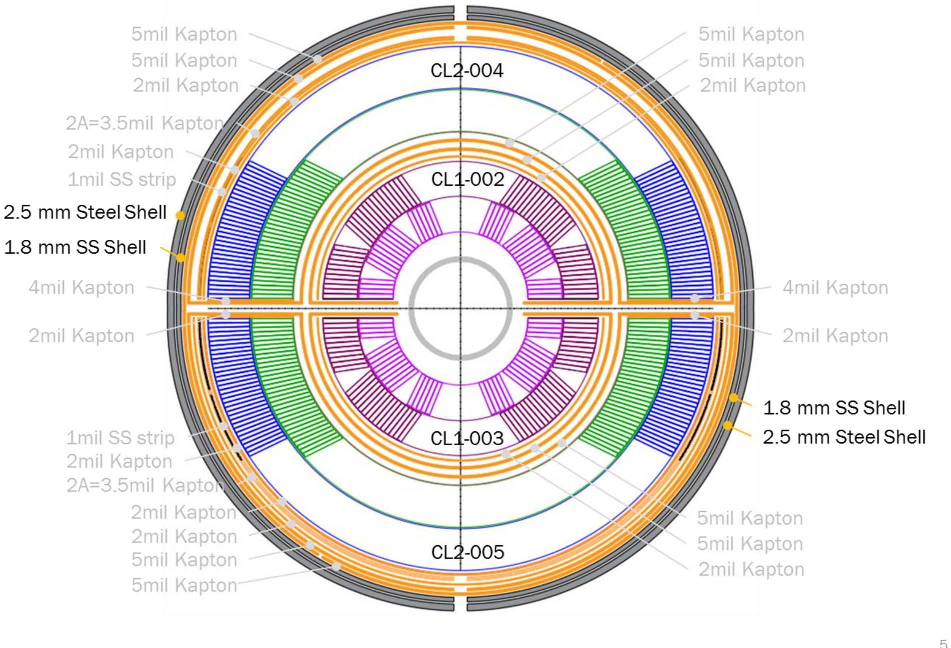
- Witness sample data are close to the target I_c
- Good reproducibility of witness sample data for IL and OL coils
- Magnet short sample limit: 15.16 T @4.5K and 16.84 T @1.9K

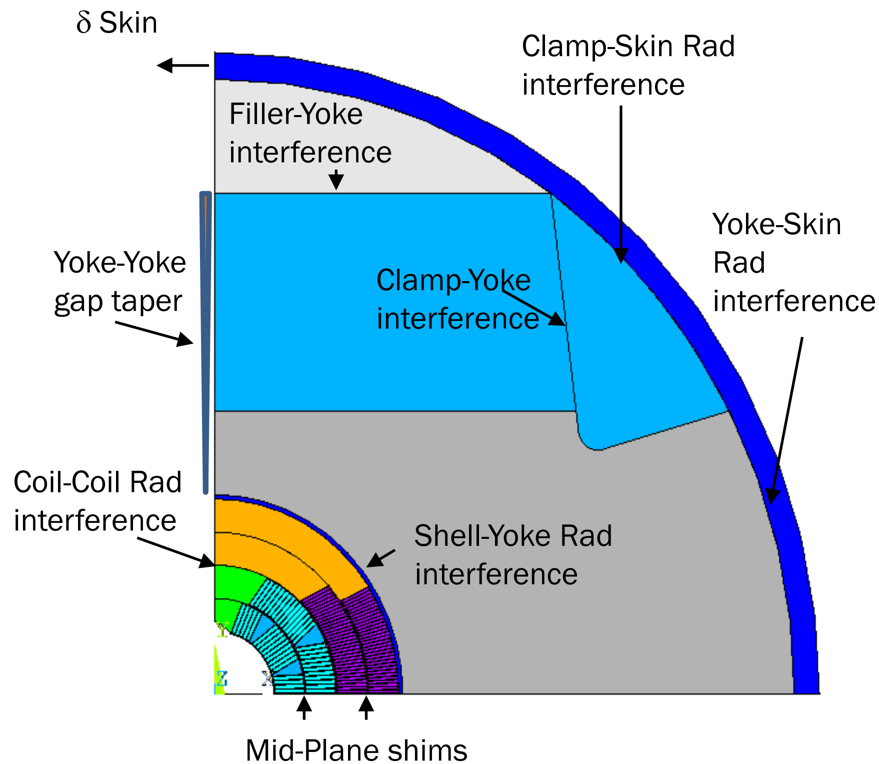
U.S. MAGNET DEVELOPMENT PROGRAM

Coil interfaces analysis and optimization



Coil assembly and preload scheme





TAC recommendations

TAC members:

- Andy Lankford (UCI, Chair), Giorgio Apollinari (Fermilab), Joe Minervini (MIT), Mark Palmer (BNL), Davide Tommasini (CERN), Akira Yamamoto (KEK & CERN)

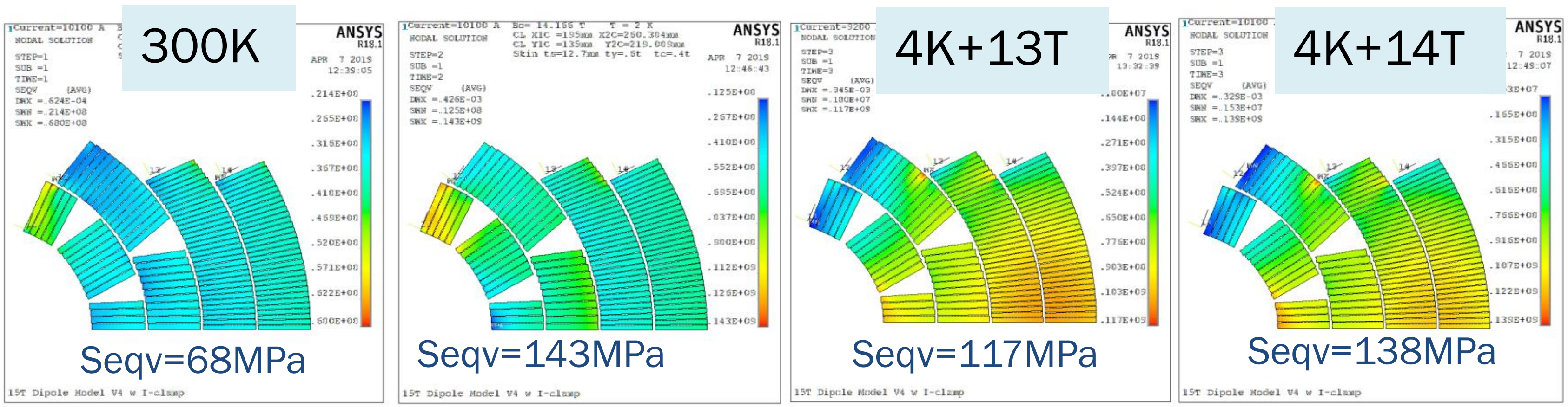
Report of the Technical Advisory Committee for the U.S. Magnet Development Program

February 22, 2019

Recommendations:

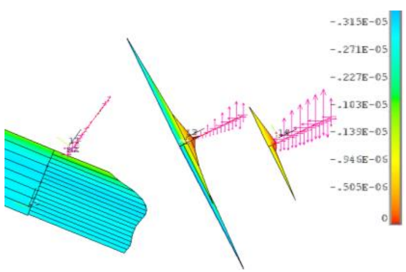
- Maintain as the priority for the cos-theta approach using the clamped mechanical structural design to realize a field of about 14 T, with special attention to mechanical stress management and control.
- Continue with demonstration of 15 T cos-theta performance only after the review of the 14 T magnet test results and feedback from the international workshop.

Target coil prestress for the first assembly

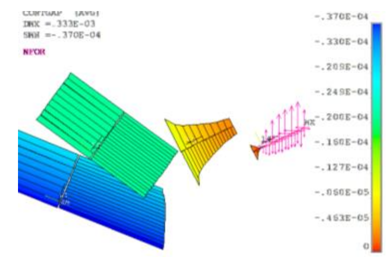


Conservative pre-stress:

- S_{max} at all steps <150 MPa



Inner Pole at 13T
Gap=0.003mm

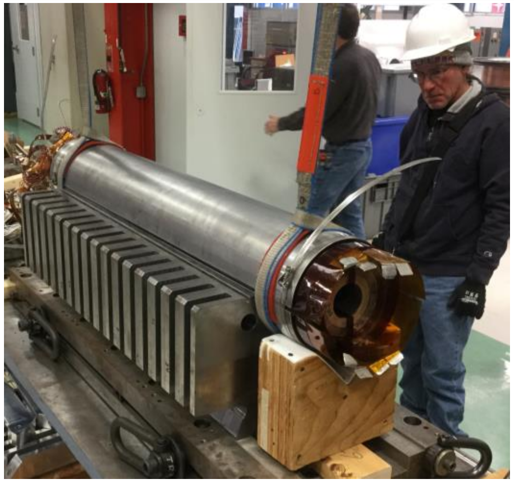


Inner Pole at 14T
Gap=0.037mm

Courtesy I. Novitski

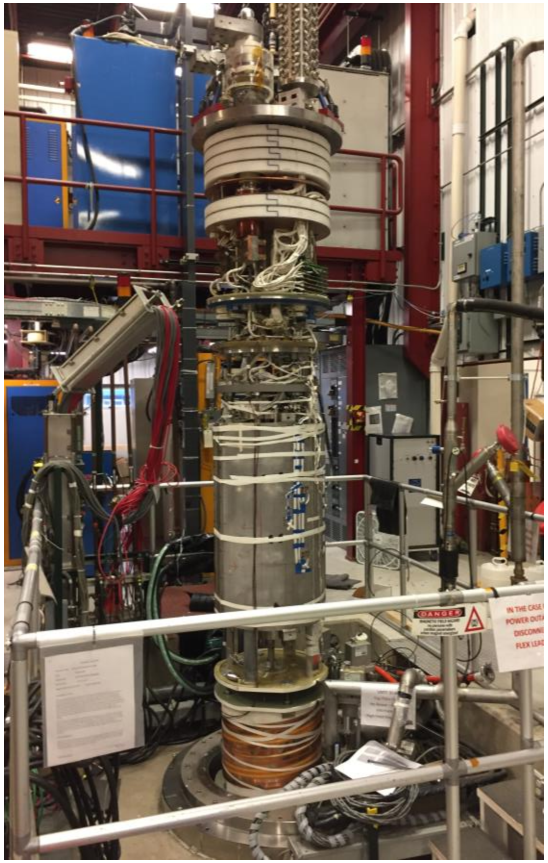
U.S. MAGNET DEVELOPMENT PROGRAM

Coil assembly, yoking and skinning





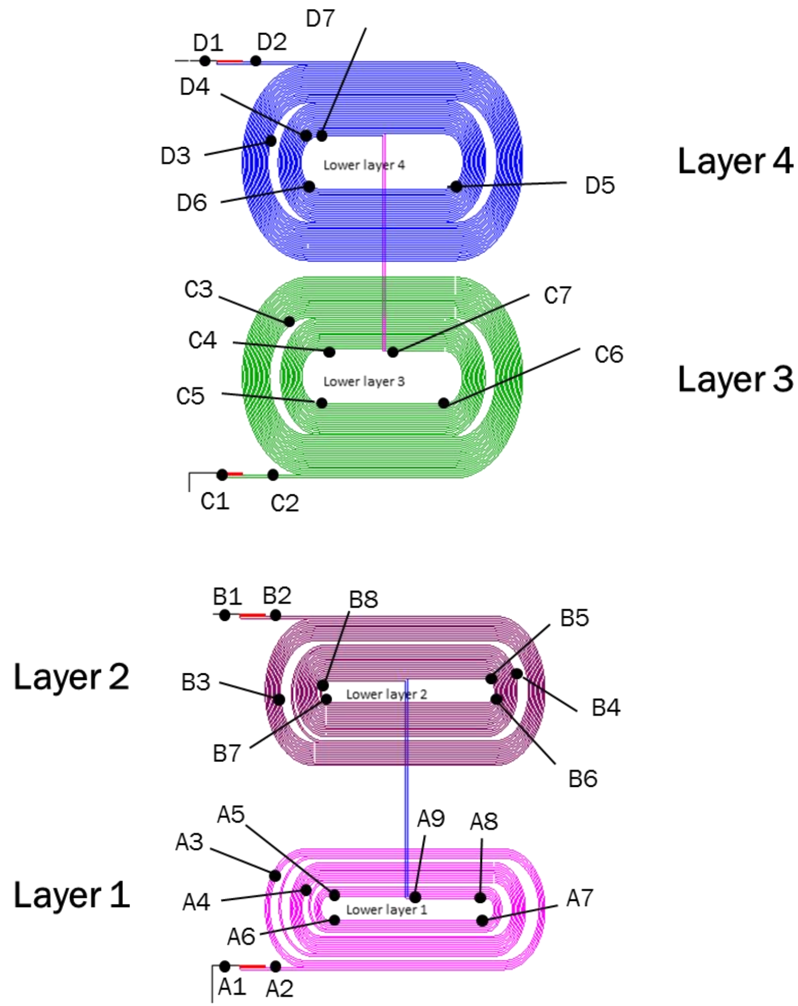

Magnet transportation and test preparation



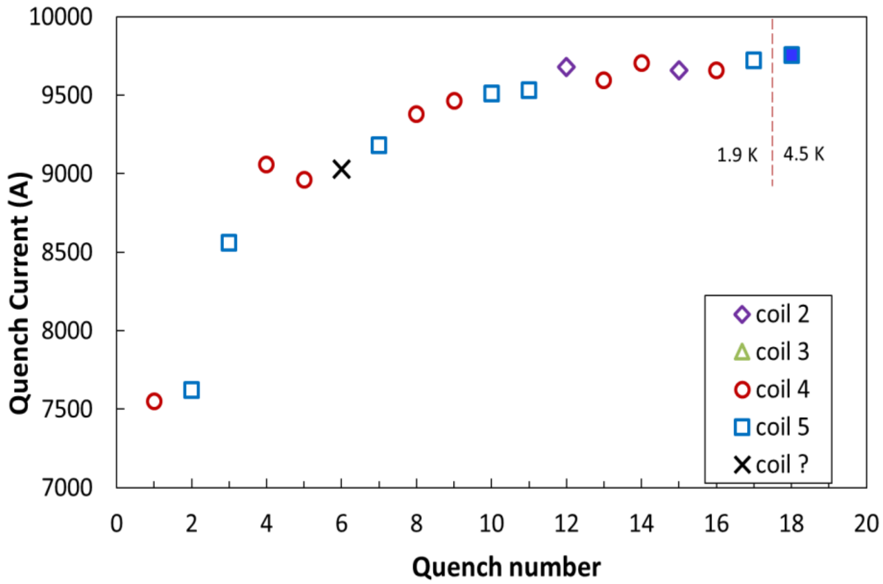
Test preparation ~1.5 months

Instrumentation

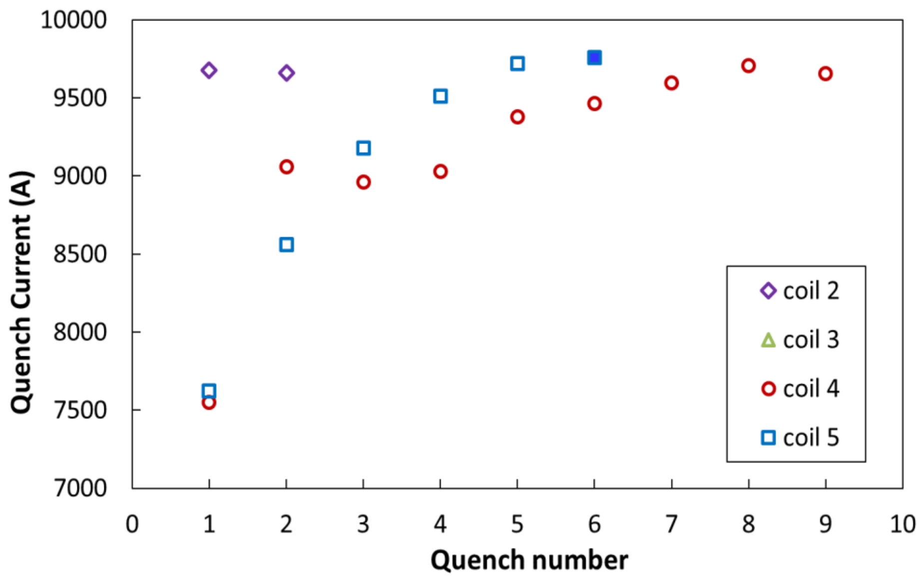
- Voltage taps on all coil layers
  - one dead and one inactive (both by-passed by using longer segments)
- Strain Gauges
  - skin gauges: OK
  - bullet gauges: two (on different bullets) dead
  - pole gauges: layer 3 and 4 all gone or inactive, layer 1 are OK
  - coil gauges: one switched off (problems during ramp up), another off for technical reasons (could be recovered if needed)
- Quench antennas
  - only sensitive to quenches in Layer 1 (didn't happen yet)
- Acoustic sensors
  - not useful data (very noisy signal)



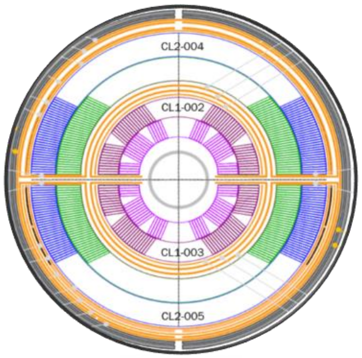
Magnet training



Courtesy S. Stoynev and G. Chlachidze



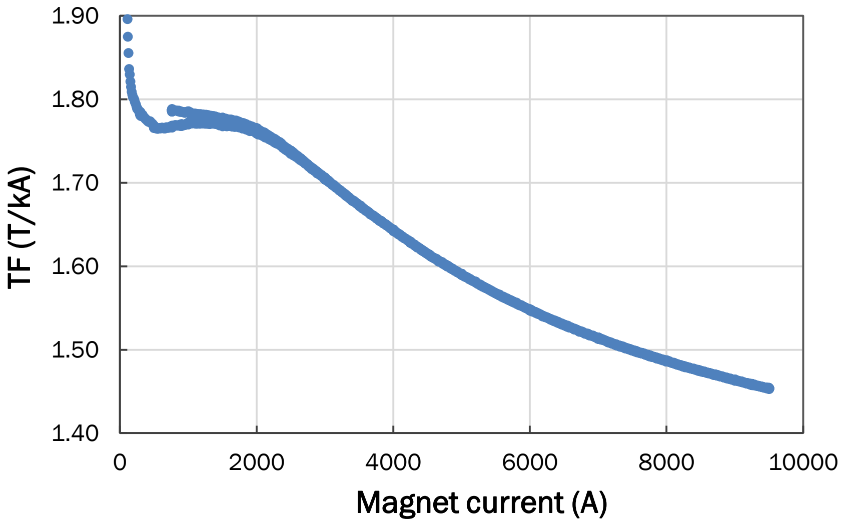
- Only 2 quenches in IL coil 2, no quenches in coil 3
- OL quenches are equally distributed between coil 4 and coil 5
- Quenches are in both layers 3 and 4 mostly in the LE
- Highest achieved quench current 9758 A at 4.5 K
- Magnet quenching was stopped after reaching the goal of ~14 T to avoid coil damage

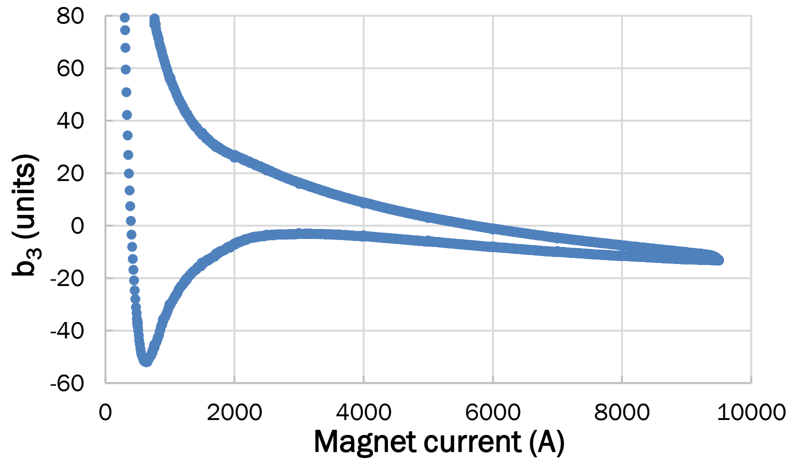


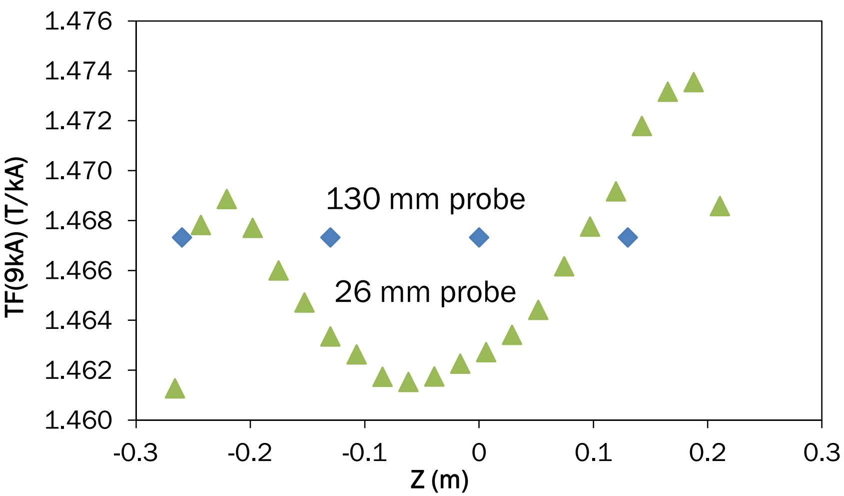
U.S. MAGNET DEVELOPMENT PROGRAM

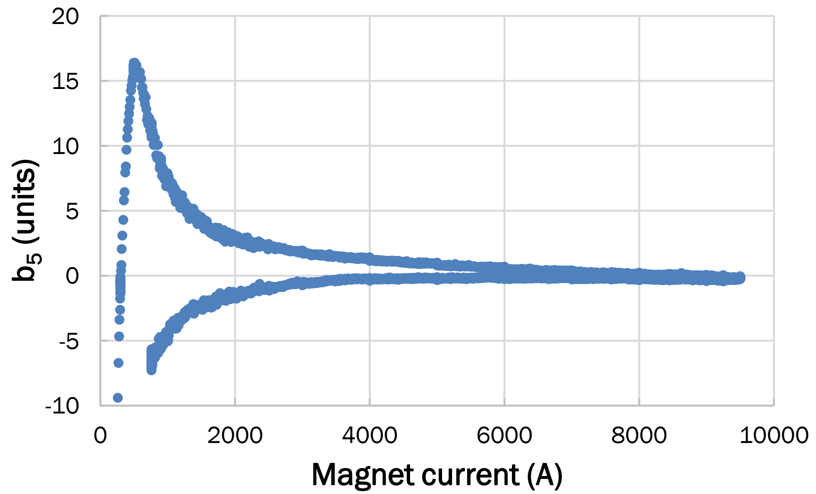
Magnetic measurements

Courtesy J. DiMarco and T. Strauss

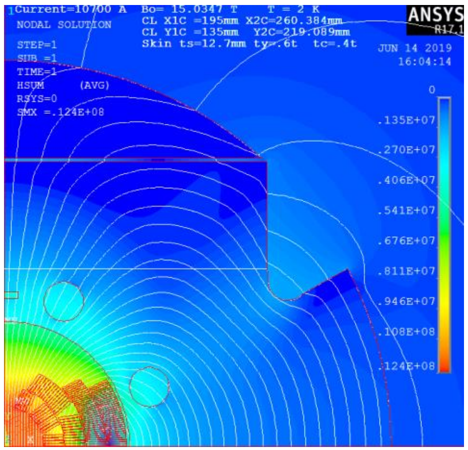




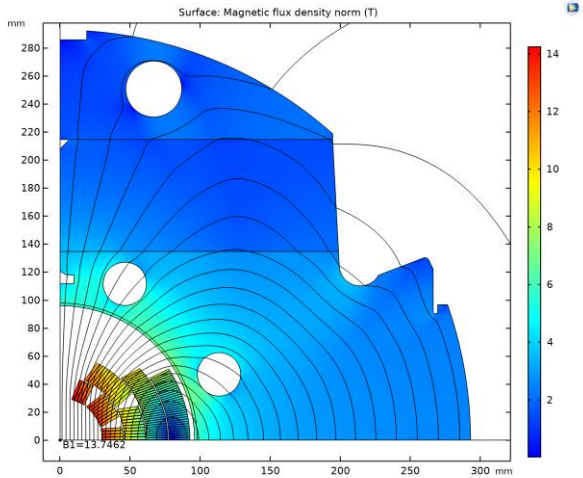


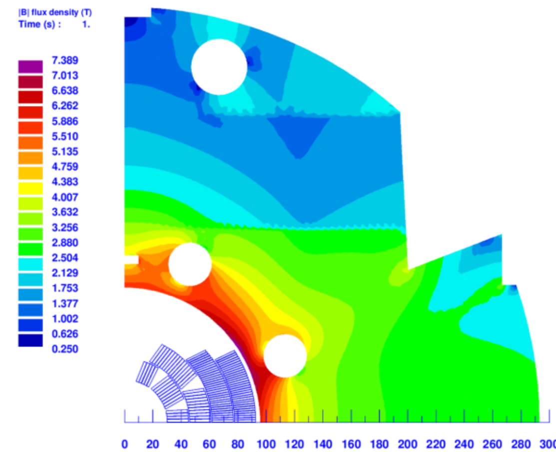


TF analysis and calibration



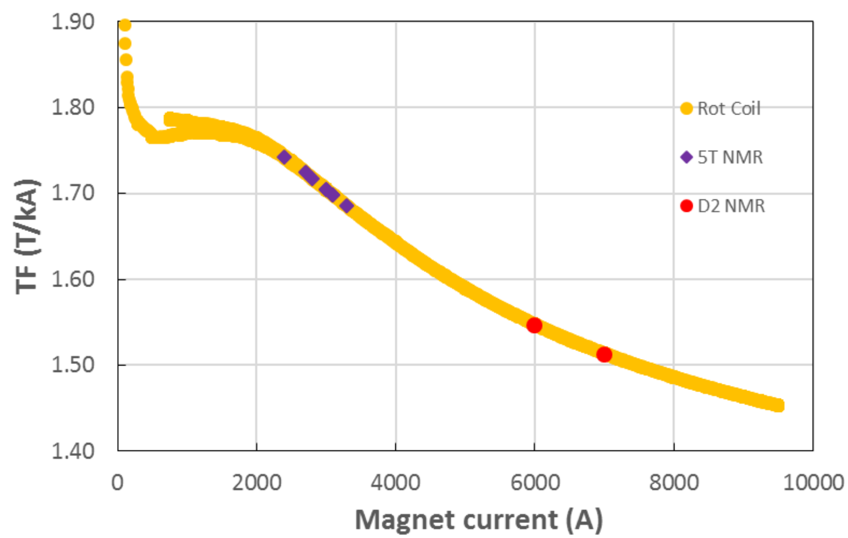
Courtesy I. Novitski





Courtesy V.V. Kashikhin

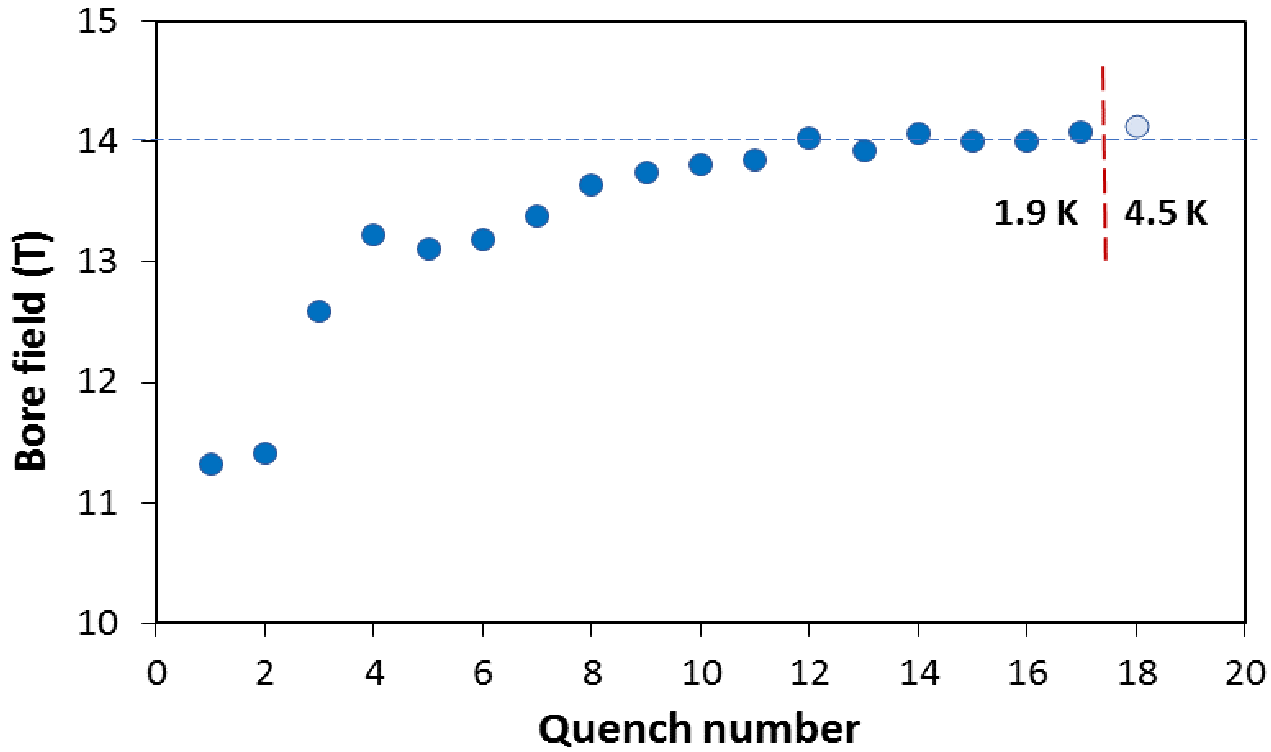
- **2D and 3D analysis has been updated based on the actual yoke material properties and the final magnet geometry**
- **Measurements have been verified with NMR probes (provided by GMW)**



Courtesy T. Strauss and M. Tartaglia

U.S. MAGNET DEVELOPMENT PROGRAM

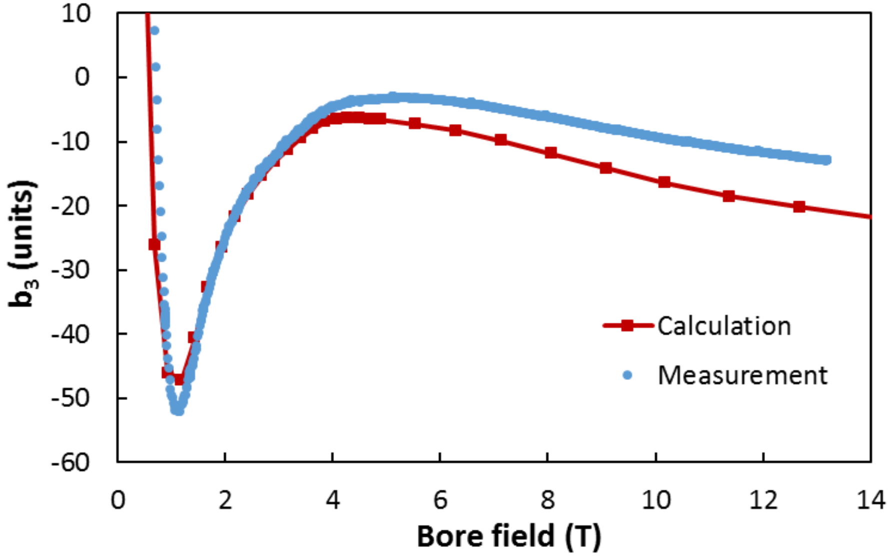
Maximum field achieved

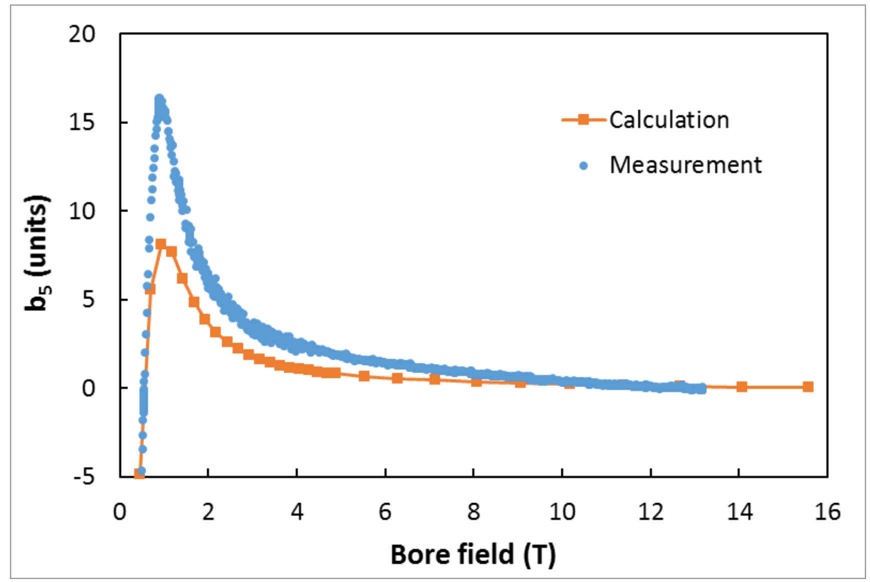


- First quenches above 11 T
- Maximum bore field at 4.5 K
  - measured 14.10±0.04 T
  - calculated (COMSOL, V.V. Kashikhin) 14.112 T

Harmonics analysis

- Predictions: V.V. Kashikhin et al., 2016





Geometrical harmonics at R_{ref}=17 mm (I=2.5 kA)

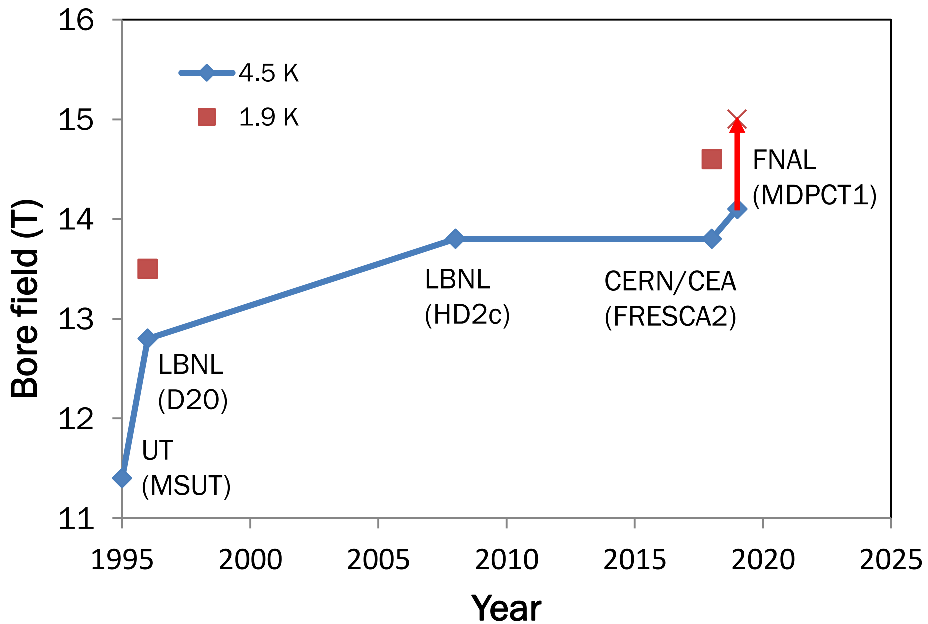
n	2	3	4	5	6	7	8	9	10
b_n	0.8	8.8	-0.4	0.7	0.1	1.0	0.0	0.2	-0.4
a_n	-2.2	-3.5	0.3	0.1	0.1	0.1	-0.1	0.2	-0.3

Summary and next steps

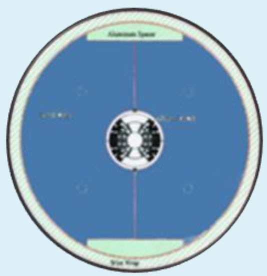
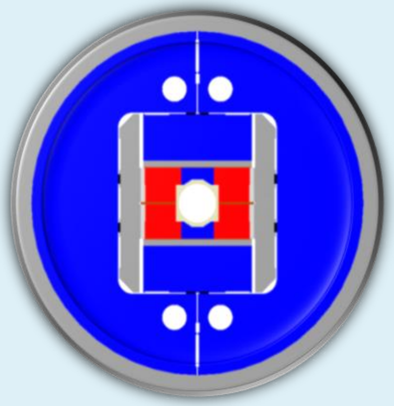
- **1-m long 15 T dipole model (MDPCT1) has been developed, fabricated and first tested at Fermilab (June 2019)**
- **The goals of the first test have been achieved**
  - **graded 4-layer coil design, innovative support structure and magnet fabricated procedure tested**
  - **B_{max} = 14.10±0.04 T at 1.9 and 4.5 K – *record field at 4.5 K for accelerator magnets!***

Next steps

- Magnet re-assembly
  - coil pre-load increase to the level sufficient to achieve the goal of 15 T
  - improve instrumentation
- Magnet second test in the fall-winter of 2019



Record Nb_3Sn magnet parameters

Parameter	D20 (LBNL)	HD2 (LBNL)	FRESCA2 (CERN)	MDPCT1 (FNAL-MDP)
				
Test year	1997	2008	2017	2018 (plan)
Max bore field [T]	13.35 (14.7*)	15.4	16.5 (18*)	15.2 (16.5*)
Design field B_{des} [T]	13.35	15.4	13	15
Design margin B_{des}/B_{max}	1.0 (0.9*)	1.0	0.8 (0.7*)	0.96 (0.89*)
Achieved B_{max} [T]	12.8 (13.5*)	13.8	13.9 (14.6)	14.1
St. energy at B_{des} [MJ/m]	0.82	0.84	4.6	1.7
F_x/quad at B_{des} [MN/m]	4.8	5.6	7.7	7.4
F_y/quad at B_{des} [MN/m]	-2.4	-2.6	-4.1	-4.5
Coil aperture [mm]	50	45	100	60
Magnet (iron) OD [mm]	812 (762)	705 (625)	1140 (1000)	612 (587)

Introduction

- Nb_3Sn accelerator magnet history
  - 1967 – the first Nb_3Sn quadrupole model
  - 1989 – the first 9.5 T dipole model
  - 2018 – record dipole field of 14.6 T (FRESCA2, CERN)
- The book
  - ~450 pages on Nb_3Sn accelerator magnet (dipoles) designs, technologies and performance
  - written by world experts in Nb_3Sn accelerator magnet technologies
  - open access
  - available online in August 2019